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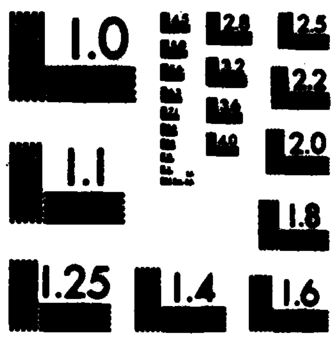
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US Army Corps of Engineers
Construction Engineering Research Laboratory

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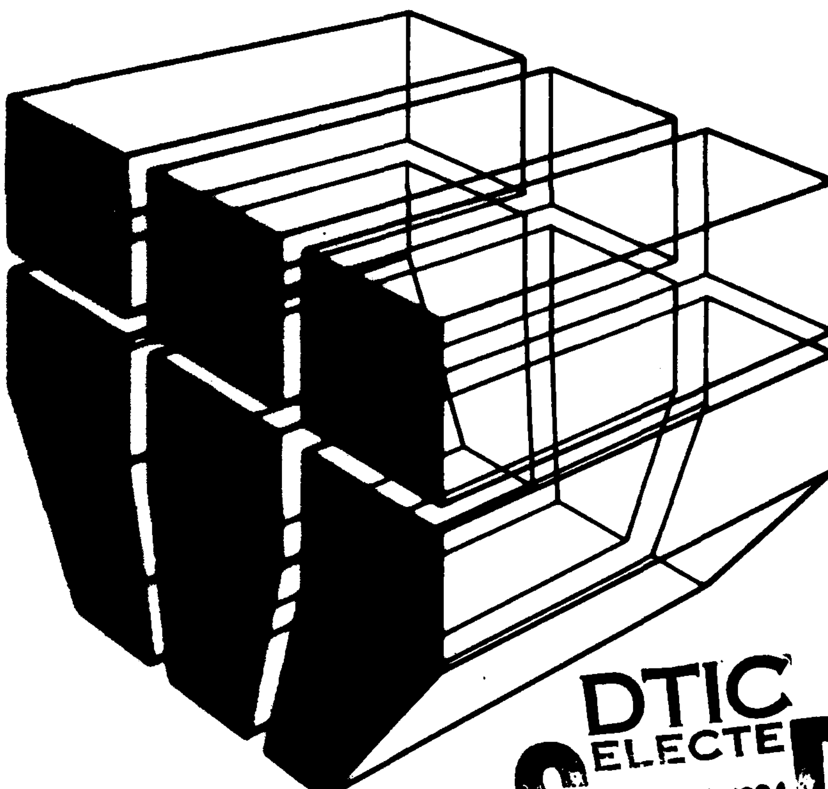
June 1984
Training Area Impact Prediction

(12)

DEVELOPMENT OF PREDICTION TECHNIQUES FOR SOIL LOSS AND SEDIMENT TRANSPORT AT ARMY TRAINING AREAS



by
Robert E. Riggins
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This report describes the selection of analytic techniques for predicting physical land degradation that results from training activities at Army installations. The nature of this degradation in terms of soil loss and sediment transport is discussed, and the processes and various analytic techniques used to model them are examined. Techniques judged suitable for predicting physical degradation of Army lands are identified. These techniques will be integrated into a comprehensive computer-based analytic tool for use at Army installations.

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FOREWORD

This study was performed by the Environmental (EN) Division of the U.S. Army Construction Engineering Research Laboratory (CERL) for the Assistant Chief of Engineers, Office of the Chief of Engineers (OCE), under Project 4A762720A896, "Environmental Quality of Military Facilities"; Technical Area A, "Installation Environmental Management Strategy"; Work Unit 026, "Training Area Impact Prediction." Mr. Donald Bandel, DAEN-ZCF-B, was the OCE Technical Monitor.

Dr. R. K. Jain is Chief of CERL-EN. COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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DEVELOPMENT OF PREDICTION TECHNIQUES FOR SOIL LOSS AND SEDIMENT TRANSPORT AT ARMY TRAINING AREAS

1 INTRODUCTION

Background

Army installations have two primary environmental concerns: maintaining the utility of training lands and protecting the environment in accordance with national environmental policy.[1] These concerns need not conflict. Research directed toward maintenance of the training mission can also result in environmental protection when training lands are well maintained.

Maintenance of training areas has growing importance for two reasons. The acquisition of additional land is difficult at most installations because of regulatory, economic, and environmental factors. In addition, new weapons and training practices require larger land areas and often use the land more intensively than in the past.

The effects of training on land vary greatly and can lead to physical, chemical, and biological degradation. Physical degradation typically changes land morphology–vegetative cover, soils, and slope-relief properties. This results in changes in runoff from rainfall and the related processes of soil erosion and sediment transport. One major environmental problem that can result is lower water quality in the streams collecting runoff. The other major problem is the loss of topsoil, which affects soil productivity and vegetative cover and can lead to gully formation. This problem directly affects the training mission by reducing the realism and quality of the exercises.

The Army controls about 5.6 million acres of land suitable for unit maneuver.[2] Another 2.8 million acres consist of impact areas and about 300,000 acres support urban-like cantonments. The amount of soil loss occurring on these areas is not known. Although erosion research has traditionally been directed toward sediment production in agricultural and urban areas, recent studies have revealed the potential for erosion problems there. These training areas particularly need maintenance recommendations.

Objective

The objective of this research is to develop a computer-based procedure for predicting physical, chemical, and biological degradation at Army training areas. The objective of the phase of study reported here was to review and evaluate available prediction techniques for erosion – the net effect of physical degradation. This knowledge will be used in developing a comprehensive, analytic method for predicting soil loss and sediment transport. The method will be useful for Army training area maintenance and environmental impact analysis. Future phases of this research will focus on methods for predicting chemical and biological degradation.

Approach

The techniques for predicting erosion were analyzed. The complexity of each method was compared to the unique erosion prediction requirements resulting from activities at Army installations. These requirements were established from visits to field sites. Theoretical analysis was used to formulate a comprehensive, analytic package for predicting physical degradation.

From these analyses, interactive computer programs were developed for using the Universal Soil Loss Equation (USLE), interval USLE, construction USLE, and runoff USLE models. Work continues on providing the necessary precipitation data bases so that all Army training installations can use these models. Characterizing a representative storm is critical to this effort. User guidance for the physical degradation model system will be developed in FY84, and the system will become operational. The next phase of development will be to modify the Colorado State University models to reflect the stochastic nature of hydrologic processes. The erosion-related rational threshold values will also be tested. Finally, work will continue on chemical and biological degradation analysis techniques.

Mode of Technology Transfer

The computer program implementing the techniques described in this report will be added to the Environmental Technical Information System.[3] Army guidance for training area impact prediction will be

[1] AR 200-1, *Environmental Protection and Enhancement* (U.S. Department of the Army (DA), 15 July 1982).

[2] TC 25-1, *Training Land* (Department of the Army, 4 August 1978).

[3] R. Webster, Rikki L. Welsh, and R. Jain, *Development of the Environmental Technical Information System*, Interim Report E-52/ADA0096681 (U.S. Army Construction Engineering Research Laboratory [CERL], April 1975).

included in a technical manual planned as part of CERL's training area maintenance research.

2 PHYSICAL DEGRADATION PROCESSES

"Physical degradation" as used here includes all processes associated with detachment and transport of soil by water. To better understand how available prediction techniques are assessed, these processes should be explained. The term "erosion" can be used to describe the net effect of physical degradation. The detachment and transport of soil in upland areas of a watershed is called "soil loss," whereas the transport of sediment to channels is called "delivery." The quantity of sediment measured at a point along the channel system is termed "sediment yield." In the literature, these definitions may be different or interchanged, but they will be used in this report as defined above.

Erosion of Soil by Water[4]

Figure 1 shows the rainfall-erosion process. When a raindrop strikes the soil, it loosens soil particles, and splash water from the impact carries the particles away.

[4] L. D. Meyer, G. R. Foster, and J. M. Komkens, "Source of Soil Eroded by Water from Upland Slopes," in *Present and Prospective Technology for Predicting Sediment Yields and Sources*, ARS-S-40 (U.S. Department of the Army, June 1975), pp 177-189; D.D. Smith and W. H. Wischmeier, "Factors Affecting Sheet and Rill Erosion," *Trans. Am. Geophys. Union*, Vol 38, No. 6 (December 1957), p 889.

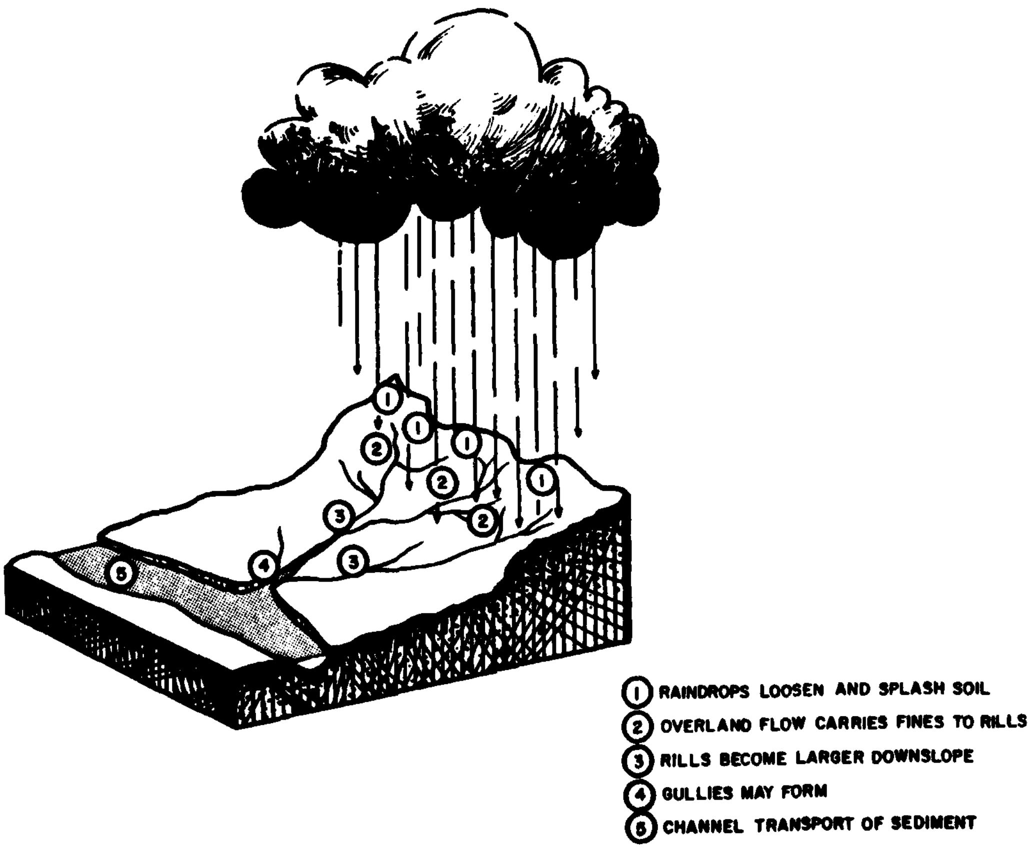

Figure 1. Erosion and transport of soil on a watershed.

As more raindrops strike the soil, there is a net downslope movement of soil particles. Overland sheet flow begins after initial losses such as surface depressions and interception by vegetation are satisfied. This flow carries away loosened soil particles. As flow coalesces, rills form (small streams of water flowing over the soil); the rills become larger as the energy of the flowing water detaches and carries away more soil particles. Overland flow eventually reaches a well-defined channel and any sediment that has not settled out somewhere on the watershed is carried away.

The detachment of soil by raindrop impact and transport of soil by raindrop splash and sheet flow is called interrill erosion. During the early stages of a rainstorm, these are the most influential forces, As a sheet or shallow layer of water forms, the effect of raindrop impact declines because the sheet absorbs the impact energy. Sheet flow usually does not provide enough energy to detach soil particles but transports the finer particles loosened by raindrop impact. This erosion process is important because the finer particles remain in suspension and are carried farther through the stream channel system. They also have a high tendency to absorb pollutants such as pesticides and fertilizers.

Additional processes begin when rills form. The energy of concentrated moving water can detach large soil particles and transport greater sediment loads. Longer slope lengths allow the formation of larger rills, increasing the energy of runoff and its transport capacity. A qualitative distinction between rills and gullies is that gullies are too large to be removed by normal agricultural tilling. As rills grow larger, they become the main sediment sources. Slope shape also has influence as convex slopes reduce erosion rates at the bottom whereas concave slopes allow a more rapid and erosive flow. The various energy sources and factors affecting soil erosion and sediment yield are shown in Figure 2.

Erosivity of Rainfall and Runoff

The first relationships expressing erosion by rainfall and runoff were parametric and lumped the two into a rainfall erosion parameter (R). Musgrave found erosion (E) proportional to the maximum precipitation in any 30-minute period (P_{30}), expressed as $E \alpha P_{30}$ 1.75.[5] This approach did not consider site differences in the number of erosive rainstorms and their expected distribution during the year.

Erosivity is not necessarily uniformly distributed throughout the year. Average distribution of erosivity can also differ among climatic regions as shown in Figure 3. Monthly values were computed and expressed as percentages of the location's average annual erosion index (EI). Monthly percentages are shown plotted cumulatively against time.

Winter precipitation in the form of snow or light rain, may show small percentages of erosion for most of the season. Yet, on frozen soil, snow melt or low intensity rainfall may cause substantial erosion. This type of erosivity should be added to the EI value to obtain total erosivity. It must also be shown in the monthly distribution of erosivity.

Wischmeier and Smith determined that soil losses are directly proportional to the product of two rainstorm properties: total kinetic energy (KE) and the maximum 30-minute intensity (I_{30}) (expressed as EI):[6]

$$KE = 916 + 331 \log_{10} I_{30}. \qquad \text{[Eq 1]}$$

where: *KE = rainfall kinetic energy*
I_{30} = maximum 30-minute rainfall intensity (in./hr).

This value was considered to include raindrop impact and turbulence of runoff. Summing EI values gives the erosivity of rainfall for an interval.

Thus, the R factor depends solely on rainfall intensity. Hotes described the R factor in terms of intensity for two types of U.S. rainfall patterns as:[7]

$$\text{Type I, } EI/100 = 15P^{2.2}/H^{0.6065} \qquad \text{[Eq 2]}$$

(Hawaii, Alaska, Coastal side of Sierra Nevadas and Cascade Mts in California, Oregon and Washington)

[5]G. W. Musgrave, "The Quantitative Evaluation of Factors in Water Erosion: A First Approximation," *J. Soil Water Conserv.*, Vol 2, No. 3 (July 1947), pp 133-138.

[6]W. H. Wischmeier and D. D. Smith, "Rainfall Energy and its Relationship to Soil Loss," *Trans. Am. Geophys. Union*, Vol 29, No. 2 (April 1958), pp 285-291.

[7]F. L. Hotes, K. H. Ateshian, and B. Sheikh, *Comparative Costs of Erosion and Sediment Control*, EPA 430N9-73-016 (U.S. Environmental Protection Agency [EPA], July 1973).

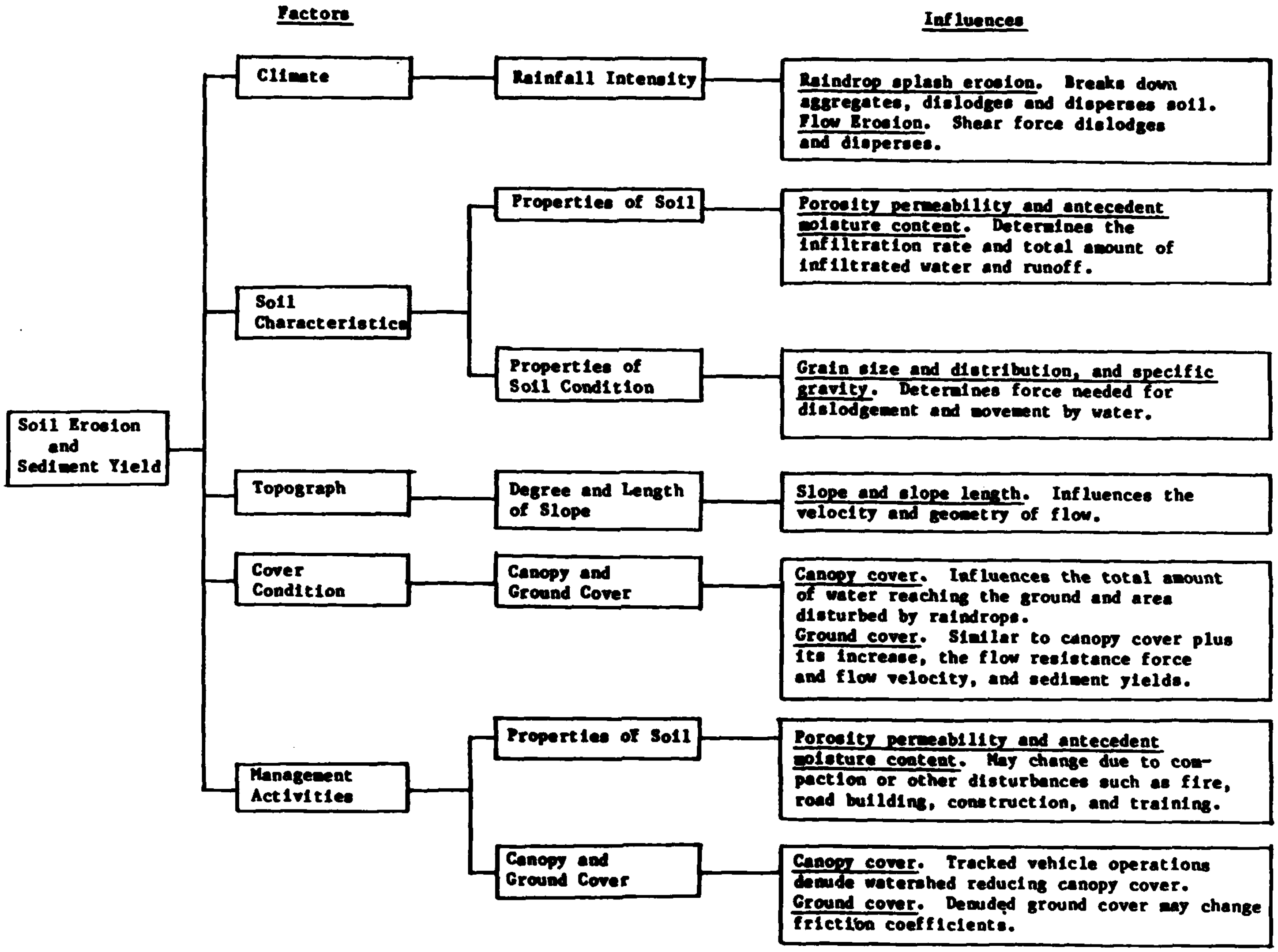

Figure 2. Energy sources and factors influencing soil erosion and sediment yields (adapted from A. W. Johnson, "Highway Erosion Control," *Trans. Am. Soc. Agric. Eng.* [1961], pp 144-152).

$$\text{Type II, } EI/100 = 19.25P^{2.2}/H^{0.4672} \quad \text{[Eq 3]}$$
(Other areas)

where EI/100 = R factor
P = depth of rainfall (in.)
H = duration of rainfall (hr).

The two EI methods have comparable accuracy, but Wischmeier and Smith's method requires that rainfall distribution be known whereas Hotes' does not.[8]

The use of EI as an expression for the R factor was modified by Onstad and Foster to include the erosivity of runoff. The new factor (W) is expressed as:[9]

$$W = .5R + aQq_p^{1/3} \quad \text{[Eq 4]}$$

where R = EI units
a = constant
Q = total runoff volume (in.)
q_p = peak rate of runoff (in./hr).

The coefficients are evaluated assuming that under certain conditions, detachment by rainfall and runoff is about evenly divided. Williams used a similar Q-q_p relationship for watersheds in Texas and Nebraska that eliminates R altogether,[10] and is intended to predict sediment yield as well as erosion.

Meyer and Wischmeier developed a flow chart for the detachment and transport processes (Figure 4).[11] They found that rainfall effects dominate at the top of slopes and runoff dominates beyond some point downslope. Also, detachment capacities are greater than transport capacities on upper portions of moderate slopes.

The relative rill-interrill contribution is an important source of sediment. Foster et al.[12] derived a relationship that approximates the ratio of rill erosion to interrill erosion for a segment, j, where detachment rate is at capacity:

$$B_j = \frac{(X_j^2 - X_{j-1}^2)(0.043S_j^2)}{72.6\,(X_j - X_{j-1})(0.3S_1 + 0.43)} \left(\frac{Kr}{Ki}\right) \times \left(\frac{15Qq_p^{1/3}}{0.5R}\right)_j \quad \text{[Eq 5]}$$

where B_j = ratio of rill to interrill erosion for segment j
X_j = distance from upper end of slope to lower end of segment j
S = percent slope
Kr/Ki = ratio of rill to interrill soil erodibility
= 2 for soils highly susceptible to rilling
= 1 for soils moderately susceptible to rilling
= 0.5 for soils resistant to rilling
Q = storm runoff volume (in.)
q_p = storm peak runoff rate (in./hr)
R = storm rainfall factor in EI units.

The ratio can be used to determine the relative quantities of soil detached and can be summed for the slope.

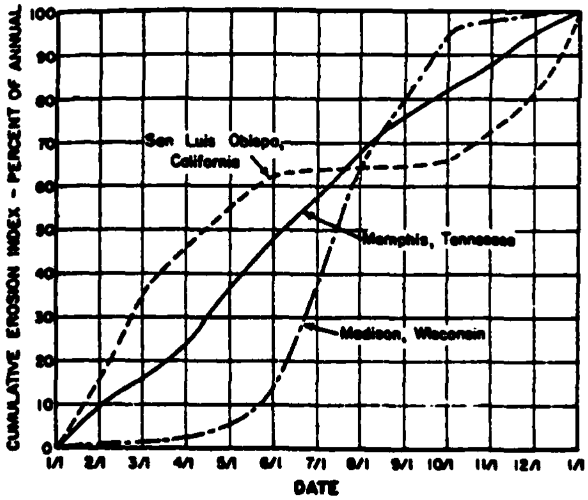

Figure 3. Typical EI-distribution curves for three rainfall patterns (from W. H. Wischmeier and D. D. Smith, *Predicting Rainfall Erosion Losses–A Guide to Conservation Planning* (Agriculture Handbook 537 [U.S. Dept. of Agriculture (USDA), 1978]).

[8] J. Bhutani, et al., *Impact of Hydrologic Modifications on Water Quality*, EPA 600 2-75-007 (EPA, April 1975).

[9] C. A. Onstad, and G. R. Foster, "Erosion Modeling on a Watershed," *Trans. Am. Soc. Agri. Eng.* (1975), pp 288-292.

[10] J. R. Williams, "Sediment Yield Prediction With Universal Equation Using Runoff Energy Factor," in *Present and Prospective Technology for Predicting Sediment Yields and Sources*, ARS-S-40 (DA, June 1975), pp 244-252.

[11] L. D. Meyer and W. H. Wischmeier, "Mathematical Simulation of the Process of Soil Erosion by Water," *Trans. Am. Soc. Agric. Eng.* (1969), pp 754-758.

[12] G. R. Foster and W. H. Wischmeier, "Evaluating Irregular Slopes for Soil Loss Prediction," *Trans. Am. Soc. Agric. Eng.* (1974).

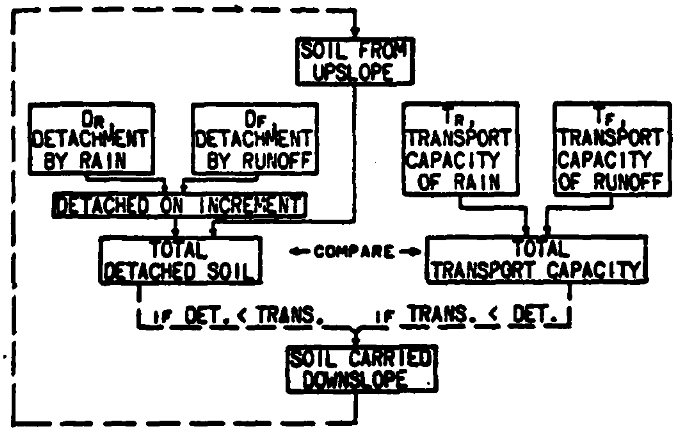

Figure 4. The soil erosion process (from L. D. Meyer and W. H. Wischmeier).

Modifiers of Rainfall-Runoff Erosion

The previous discussion assumed that rainfall was falling on exposed soil, which often is not the case. Vegetation intercepts rainfall and retards flow, and root systems tend to hold soil in place, thereby increasing infiltration rates. The effect vegetation has on soil loss depends on: (1) the percentage of canopy cover, (2) the amount of vegetation cover in direct contact with the soil surface, and (3) effects at or beneath the surface.

Vegetation is a seasonal variable and provides different degrees of soil protection during the year. The degree of protection afforded by vegetation is related to the distribution of erosive rainfall over the year. Figure 5 shows the approximate growing season of crops and trees in north central Missouri.[13] This type of information can be compared with EI distribution curves (Figure 3) to determine the effectiveness of vegetative cover over the whole year.

The slope of the land and the length of overland flow affect the erosivity of runoff. Steep slopes can increase the velocity of runoff, whereas long slopes can allow greater rill development. These effects have been quantified in factors to adjust erosivity as follows:[14]

$$\text{Slope steepness, } S = 65.41 \sin^2\theta + 4.56 \sin\theta + 0.065 \qquad \text{[Eq 6]}$$

where θ = angle of slope (inclination from horizontal)

$$\text{Slope Length } L = (\lambda/72.6)^m \qquad \text{[Eq 7]}$$

where λ = slope length in feet
m = a constant depending on slope
= 0.5 for $\theta > 5$ percent
= 0.4 for 4.5 percent $> \theta >$ 3.5 percent
= 0.3 for 3.0 percent $> \theta >$ 1.0 percent
= 0.2 for $\theta <$ 1.0 percent

[13] R. E. Riggins and J. R. Anderson, *Investigation of the Effects of Construction and Stage Filling of Reservoirs on the Environment and Ecology: Preproject Baseline*, Technical Report N-24/E77-10220 (CERL, May 1977).

[14] W. H. Wischmeier and D. D. Smith, 1978.

The average slope length and gradient of a watershed can be determined using the contour-extreme point and the contour-length methods.[15] The contour-extreme point equation is:

$$\lambda = \frac{LC \times LB}{2EP\sqrt{LC^2 - LB^2}} \qquad \text{[Eq 8]}$$

where LC = the total length of all contours
EP = the number of extreme points on the contours
LB = the total length around the base of the contour (Figure 6).

The contour-length equation for average gradient is:

$$S = \frac{.25Z(LC_{25} + LC_{50} + LC_{75})}{DA} \qquad \text{[Eq 9]}$$

where S = the slope steepness
Z = total watershed height
LC_{25}, LC_{50}, and LC_{75} = contour length at 25, 50 and 75 percent of Z
DA = the drainage area of the watershed.

There are several artificial ways to modify rainfall-runoff erosion. The watersheds can be shaped mechanically to reduce erosion. Agricultural practices such as terracing, contour plowing, and strip cropping reduce the forces of runoff. By destroying rills, tillage reduces the erosion that would result if rills were allowed to grow during successive rainstorms. During construction, flow rates can be reduced using barriers or sediment basins so that sediments settle and are trapped.

Soil Erodibility

Some soils erode more readily than others. Erodibility (K) relates well to five soil properties: (1) percentage silt plus very fine sand (<.1 mm in diameter), (2) percentage sand (.1 to 2.0 mm in diameter), (3) percentage organic matter, (4) soil structure and (5) permeability.[16] For soils less than 70 percent silt and very fine sand, an expression is:

$$100K = 2.1\, m^{1.14} (10^{-4})(12-a) + 3.25(b-2) + 2.5(c-3) \qquad \text{[Eq 10]}$$

where m = particle size parameter = percentage silt × (100 − percentage clay)
a = percentage organic matter (use 4% if greater than 490).
b = soil structure code
c = permeability code

This equation does not adequately predict K for subsoils with a high content of clay. An equation that uses terms involving soil particle size distribution and the amount of amorphous hydrous oxides of iron, aluminum, and silicon in the soil can be used.[17] The equation is:

$$K = 0.32114 + 2.0167 \times 10^{-4} M_1 - 0.14440 (\%Fe_2O_3 + \%Al_2O_3)^{?} - 0.83686 (\%S_iO_2) \qquad \text{[Eq 11]}$$

where M_1 = the sum of percentages of soil particles falling within the 2 to 100 μm and 100 to 200 μm mean diameter particle size.*

Sediment Delivery

Stormwaters eventually recede and, as flow rates decline, sediment begins to be deposited. Not all the soil lost from upland areas reaches the channel system and not all the sediment that enters the channel reaches the sea. Soil loss calculations must be adjusted to allow for deposition of sediment at the base of slopes, in the floodplains, along the stream channels, and elsewhere.

[15] J. R. Williams, and H. D. Berndt, "Determining the Universal Soil Loss Equation's Length-Slope Factor for Watersheds," in *Soil Erosion: Prediction and Control, Proceedings of the National Soil Erosion Conference* (1977), pp 217-225.

[16] W. H. Wischmeier, C. B. Johnson, and B. V. Cross, "A Soil-Erodibility Nomograph for Farmland and Construction Sites," *J. Soil Water Conserv.*, Vol. 26, No. 5 (1971), pp 189-193.

[17] C. B. Roth, D. W. Nelson, and M. J. M. Romkens, *Prediction of Subsoil Erodibility Using Chemical, Mineralogical and Physical Parameters*, EPA 600 2-74-043 (EPA, June 1974).

*Representative values of K can also be obtained for most of the soil types and textural classes from tables prepared by soil scientists who use the latest research information. Soils data from the Soil Conservation Service's Soils-5 data base at the U.S. Department of Agriculture (USDA) support center at Ames, IA, is now available in a user-friendly interactive computer format at CERL. This system contains K values for all recognized soil series in the United States.

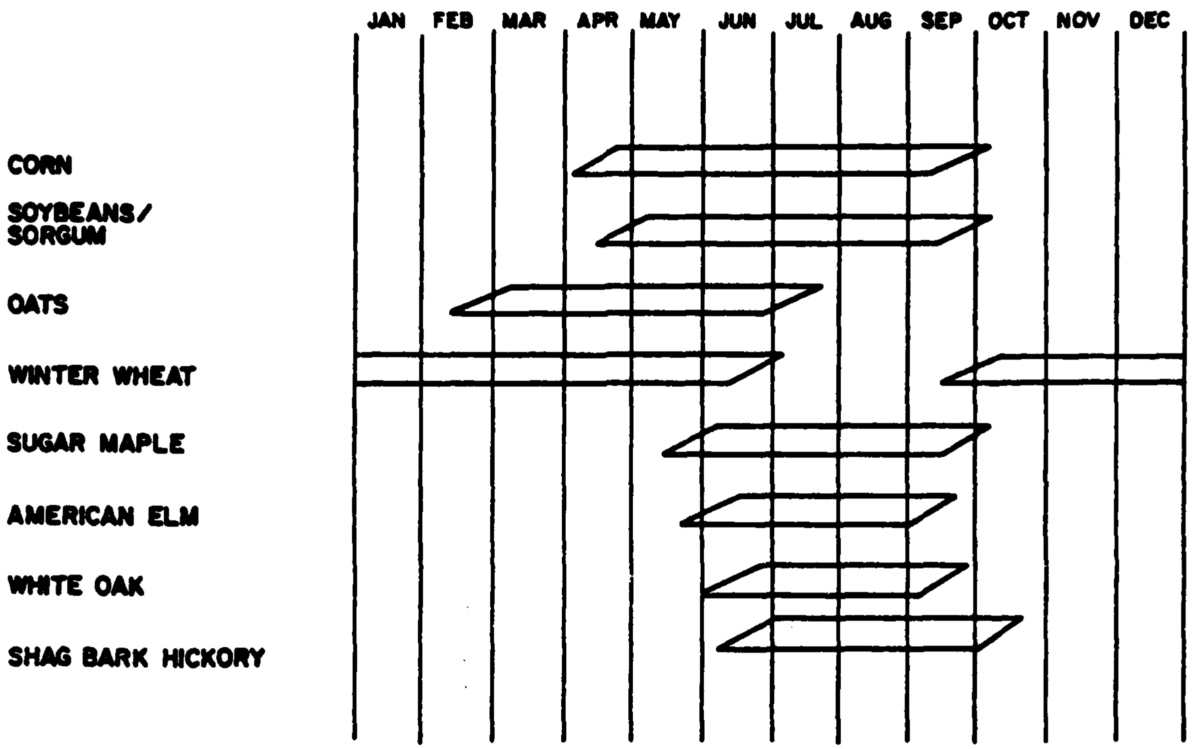

Figure 5. Approximate growing seasons of crops and trees.

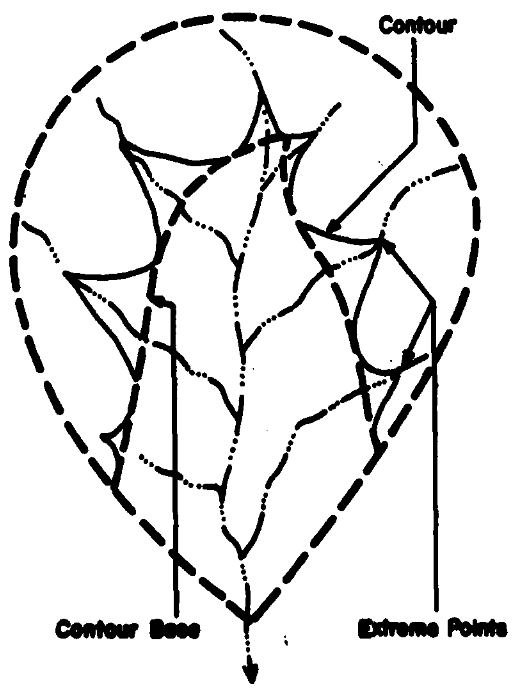

Figure 6. Example watershed showing contour extreme points and base (from J. R. Williams and H. D. Berndt).

The amount of sediment that reaches a given point is called sediment yield. The sediment yield divided by the total soil loss is called the sediment delivery ratio (DR). Many factors influence sediment yield. For example, if the source of materials is sheet erosion, only a portion may reach the channels. Also, erosion within the channel is immediately available for transport. Large amounts of eroded material that originate at some distance from the stream may contribute less sediment than a small amount of eroded material that originates close to the stream. Transport system properties tending toward higher sediment yield include high velocities, large volume of discharge, more frequent and longer storms, high channel densities (number of channels/area in the watershed), and steep channel gradients. Smaller particle size increases sediment yield because fines (generally from raindrop splash) tend to be transported more easily. Streams in watersheds with finer textured soils will have longer periods of turbidity. Of course, the more areas for deposition (such as winding, slow-moving channels), the less downstream sediment delivery.

Empirical relationships have been developed to express delivery ratios and sediment yield,[18] but these relationships apply only to specific areas. No general relationships can be stated for all areas. Watershed properties commonly used in such relationships include area, topography, shape, relief, and the relief-to-length ratio.

One problem Boyce notes with delivery ratios is that they are often related to sheet erosion reaching the channel, but not to erosion/deposition occurring in the channel system.[19] Many relations for delivery ratios use area to represent the effects of channel length, channel density, and relief, for example, but slope is a better parameter. For most areas of the country, average slope declines as area increases. Uplands thus should have higher delivery ratios and lowlands should have lower ratios. As watershed size grows, the average slope will decrease as more lower areas are involved. This fact and the channel storage (deposition) factor explain how the sediment yield for a total drainage area will be less than the sum of sediment yields for individual sub-areas.

Because delivery ratios are specific to the area for which they are developed and provide information only on long-term sediment yield, they are not of great value in predictive analysis. Another way to use delivery ratios is to couple them with soil loss prediction techniques.

Two theories have been applied to sediment movement from the watershed slopes and through the channel. The first assumes that during a storm, sediment is flushed down the channel with the flood waters. The second assumes that successive flood waves from separate storms pick up the sediment, transporting it a certain distance. However, the exact method of sediment movement is important for describing pollutant transport.

3 PHYSICAL DEGRADATION OF LAND AT ARMY INSTALLATIONS

Sediment Sources

Army installations are operated to train and support land combat forces. Typical installations include a cantonment area to house troops and provide administrative, supply, and maintenance operations much like a small civilian community. The remainder of the installation is mostly training and impact areas. Some of the land may be leased for grazing or other agricultural uses.

The greatest erosion occurs in training areas where movement of troops and vehicles results in damage or destruction of vegetation. Tracked vehicles are the most destructive and produce unique types of erosion. One conclusion from a study of erosion at Fort Polk, LA, was that as a result of sedimentation (settling of eroded soil), streams have been changed from deep, narrow, and swift running to slower, wider, and more winding with much shallower depths.[20] Depths of

[18] W. C. Ackerman, and R. L. Corinth, "An Empirical Equation for Reservoir Sedimentation," *Publication 59* (International Association of Scientific Hydrology, Commission of Land Erosion, 1962), pp 359-366; H. W. Anderson, "Flood Frequencies and Sedimentation from Forest Watersheds," *Transactions, American Geophysical Union*, Vol 30, No. 4 (August 1949), pp 567-583; S. B. Marier, "Factors Affecting Sedimentation Delivery Rates in the Red Hills Physiographic Area," *Trans. Am., Geophys. Union*, Vol 34 (August 1958), pp 669-675; J. W. Roehl, "Sediment Source Areas, Delivery Ratios and Influencing Morphological Factors," *Publication 59* (International Association of Scientific Hydrology, Commission of Land Erosion (1962), pp 202-213; V. A. Vanoni, "Sedimentation Engineering," *Am. Soc. Chem. Eng. Manuals and Reports on Engineering Practice*, No. 54 (1975).

[19] R. C. Boyce, "Sediment Routing With Sediment Delivery Ratios," in *Present and Prospective Technology for Predicting Sediment Yield*, ARS-S-40 (DA, June 1975).

[20] R. Burkhard, et al., *Present and Projected Erosion from Redleg I and Peason Ridge Areas, Fort Polk, Louisiana*, Unpublished Report (Environmental and Energy Control Office, DFAE, April 1978).

total erosion are evident in the distance between ground level and the butt swell of trees. Observations in heavy use areas showed conditions ranging from a few inches of soil loss to erosion so severe that nearly all vegetation was destroyed with some trees toppled over.

Also, during a recent ecological survey at Fort Knox, KY, observations were made on the presence, distribution, and diversity of vegetation in tracked vehicle areas.[21] Where areas had been denuded as a result of long-term training, it was estimated that soils may take 1000 years to recover by natural succession.

Unlike agricultural areas, the land in training areas is usually left untilled. As rills form, they tend to keep growing into gullies (Figure 7). Vehicles do obliterate small rills as they move through an area, but not in a systematic way that would contribute to soil conservation. The effect of tracked vehicles is a loosening of soil to a depth of a few inches and soil compaction at lower depths.[22]

Also unlike agricultural practices, training is not done only in the gently sloping areas suitable for tillage. The terrain is often rugged with steep slopes and occasional depressions. Scattered vegetation may be found around occasional large trees or along places difficult to cross. Figure 8 represents such an area.

Predicting erosion in these training areas is difficult because factors such as slope, vegetative cover, and soil erodibiity may be atypical. Other problems include the presence of many unpaved roads or tracks criss-crossing the area. Often, sites of vehicular stream crossing cause unnatural runoff focal points, which funnel sediments directly into the channel system.

A method of determining erosion from training areas using sediment catchment basins has been used in selected watersheds at Fort Carson, CO.[23] Regression analysis was performed to find a cover factor based on current training levels. Predictions then were made of erosion rates from more intense training by assuming a linear relationship between intensity of training and loss of vegetative cover.

The sediment contribution from impact areas is unknown. Where exploding shells damage vegetation and disturb the soil, the magnitude of the effect depends on the size of the charge. Here also, estimating the factors used in erosion prediction may be difficult. Impact disturbance would tend to make more material available for transport. However, the depressions created by impacts would tend to increase surface depression storage of rainfall and obstruct overland flow. Also, because inert shells are used more today, the degree of disturbance is probably lessening.

Some areas on an installation are in an essentially natural state. Surrounding an impact area is a buffer zone in which human activity is largely prohibited. These areas can be treated as idle land when predicting erosion.

Some areas are leased to agriculture. Typically, this is rangeland, but some cropland is also leased. Standard USLE erosion prediction is generally adequate for such areas.

Effects

Erosion must be related to soil loss tolerance to determine the effects on soil productivity. Slight soil loss on shallow soil over bedrock can be serious but certain deep soils can be badly eroded without serious effects on productivity. Soil loss effects are expressed as the T-factor (tolerance factor). Factors have been developed by USDA for most soil types in the United States and express the allowable annual erosion rate that will not have a long-term effect on soil productivity.

The major effect of soil erosion is the resulting sedimentation in streams and lakes. Physical effects include siltation of lakes and reservoirs, channel instability, and increased cost of water treatment. More dramatic effects occur on aquatic biota, some of which are listed in Table 1.

The concept of Rational Threshold Values (RTV) was developed at CERL to provide a technique for assessing impacts on organisms. RTVs are quantitative values that can be used to predict effects using analytic models. RTVs under consideration for point-source sediment pollution are algal growth indices for lentic systems and fish pollution levels for lotic

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[21] W. Severinghaus, R. E. Riggins, and W. Goran, *Effects of Tracked-Vehicle Activity on Terrestrial Mammals, Birds and Vegetation at Fort Knox, KY*, Technical Report N-77/ADA 073782 (CERL, July 1979).

[22] W. Severinghaus, R. E. Riggins, and W. Goran.

[23] M. P. Keowin, and H. W. West, "Environmental Baseline Descriptors for Use in Management of Fort Carson Natural Resources," Report 4, *Analysis and Assessment of Soil Erosion in Selected Watersheds*, Technical Report M-77-4 (U.S. Army Waterways Experiment Station [WES], February 1978).

Figure 7. Tracked-vehicle training area.

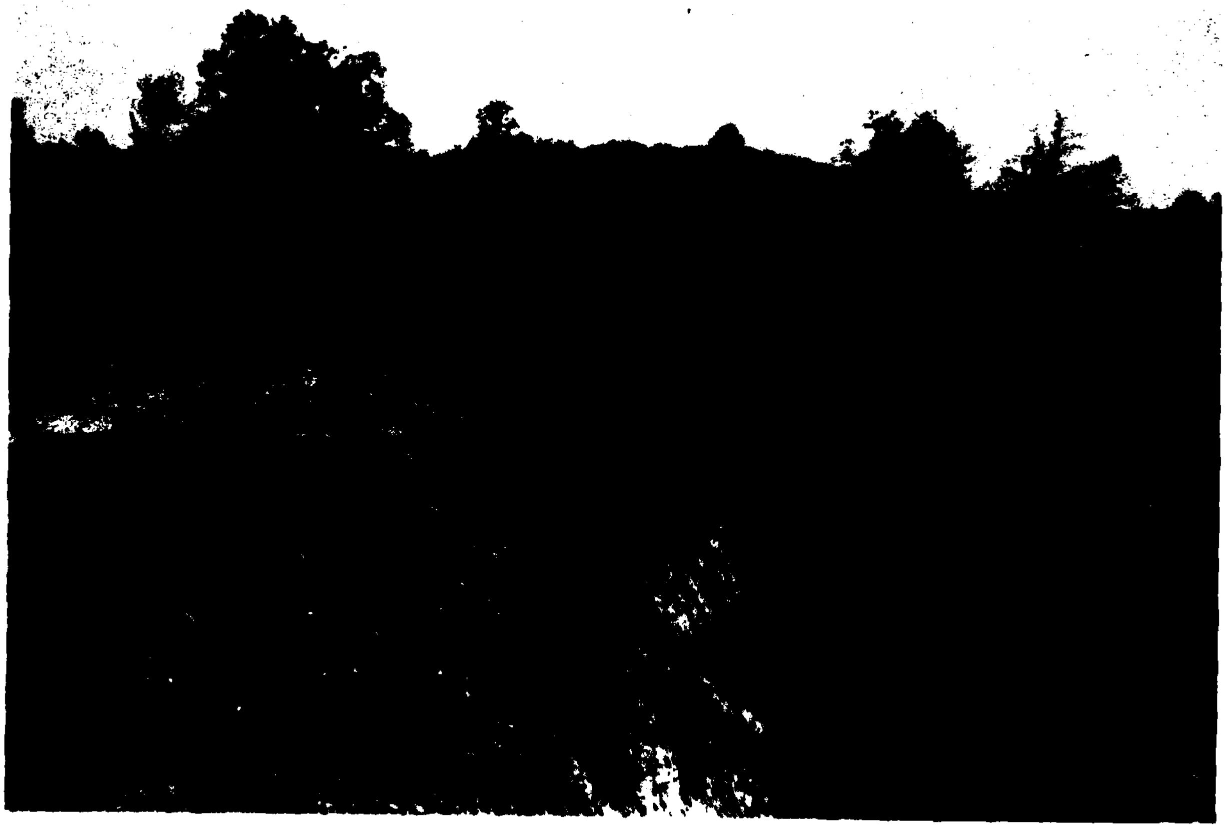


Figure 8. Formation of gullies in tracked-vehicle training area.

systems. A CERL technical report examines the feasibility of using these RTVs.[34]

4 USE OF MODELS AS ANALYTIC TECHNIQUES

Alternatives for Training Area Improvement

Several different plans would improve the utility of Army training lands. The first is to develop improved maintenance programs. This would require that land managers have methods for evaluating the condition of lands to decide when maintenance is needed. If land degrades too much, maintenance is difficult and costly.

[34] C. C. Vaughn, G. D. Schnell, and R. E. Riggins, *Feasibility of Using Rational Threshold Values to Predict Sediment Impacts from Army Training*, Technical Report N-153/A130997 (CERL, July 1983).

Table 1

Qualitative Effects of Sediment on Aquatic Biota

Plant life	
	Decrease in sunlight reaching plants, therefore a decrease in photosynthesis
	In shallow streams, changes in bottom structure resulting from siltation may alter community structure
	Community diversity may be reduced
Microinvertebrates	
	Silt-covered bottoms cannot support a normal population
	High turbidity leads to drift
	Community diversity may be reduced
Fish	
	Very high concentrations will cause death by clogging the gills
	Lower concentrations may also be detrimental when acting synergistically with other pollutants
	As turbidity rises, growth rates seem to decrease, possibly due to difficulty in finding food
	Salmonid fish will only spawn in areas free from sediment
	Fish egg and larvae development is greatly impaired by deposited silt that obstructs the flow of dissolved oxygen
	Possible migration of fish to nonturbid waters
	Since sediment can absorb other pollutants or toxicants, they may enter the food system and lead to biological magnification

On the other hand, unnecessary maintenance wastes resources.

Improved evaluation will result in a greater demand for land maintenance technology to provide effective, efficient ways to restore and maintain lands. With this increased technology, land managers would need guidance in using it. For example, they may seek information on the use of new and better vegetation species that can withstand the stresses of training.

Another way to improve these lands is by operational change. This includes more efficient use of available lands, land use rotation to let damaged areas recover, seasonal considerations to avoid use of land during sensitive times, and more effective scheduling of land use. A land rotation scheme, for example, would require nonuse of certain land areas for some time period. By keeping the restricted land areas small and scattered, however, this should have minimal effect on training.

A third plan is designed maneuver areas. The design might include requirements for type and density of vegetation, natural and constructed obstacles, line-of-sight targeting, and the capability to vary trainees' experience using different routes and approaches to targets. Several design modifications for reducing destruction and maintenance needs would be included in these requirements—for example, strategic placement of erosion controlling devices.

The emphasis of research for this report is on the first plan—improving environmental maintenance at training areas. Soil erosion at Army installations is affected by training, construction, and leased-land activities. The effects differ with each activity. For agriculture, soil loss is usually predicted on an average annual basis. Construction and training are carried out on a shorter time-frame, so seasonality and activity duration are important factors. Spatial references also change with different activities. Construction projects usually are within an area of a few acres, whereas leased-land activities involve areas ranging from tens of acres to several square miles. Training often stretches over still larger areas.

The analytic tools needed to predict erosion-related effects must therefore be designed to accommodate the different situations. To meet these requirements, prediction techniques were chosen that comprise a modeling system for erosion.

Types of Erosion Models

Methods of modeling the erosion process can be roughly classified into three groups: empirical, physical process, and stochastic.

Empirical models are based primarily on the Universal Soil Loss Equation (USLE) and its modifications. They are generally developed by relating various watershed properties to erosion using regression techniques. Although popular and easy to use, empirical models are usually based on limited data specific to a given study area. Also, they are not as useful for analysis of watershed response to changing land uses, since this generally requires data collection after the watershed has been impacted.

Physical process models are developed to represent the interaction of natural processes within the watershed. Such models use deterministic rainfall-runoff relationships as a transport medium. They also use parameters derived from analysis of sediment data to calculate soil loss. Since these models deal directly with the physical processes and not empirical data sets, they are much more useful for predicting the response of the watershed to training activities.

Stochastic models are intended to allow for the spatial and temporal randomness of hydrologic processes such as precipitation and streamflow.[25] One method of developing a stochastic model is to modify a deterministic physically based model to generate random values (within reasonable ranges) for factors that fluctuate randomly in the environment. Work with a stochastic model is in progress at CERL and will be reported in a future publication.

The models described in this research are intended for three primary users at Army installations: range officers, land managers, and environmental office personnel. Range officers are responsible for range development and management, including construction and maintenance. Water and sediment yield prediction models can be used to judge needs for environmental protection during construction and erosion prevention or control for range maintenance.

Army land managers can use water and sediment yield prediction models at least three ways. First, they can predict the impact of scheduled training on a watershed. If predicted effects exceed acceptable levels, the manager can program appropriate maintenance to restore the damage. A second use for the models is to evaluate the degree to which a given maintenance technology might reduce soil loss from a watershed. By changing relevant watershed factors, the manager can evaluate the resulting change in water and sediment yield. The third use for the models is to monitor the change in a watershed over time. By comparing watershed data from the models, the manager can determine if the watershed is improving or degrading systematically.

Environmental office personnel at installations will find the models valuable for impact assessment studies involving erosion. This might help prevent problems with high suspended solids in drinking water supplies for downstream communities.

Empirical Models

The USLE has been widely used for over 25 years.[26] The Musgrave relationship previously discussed was refined by Wischmeier and Smith to improve the rainfall factor, add a conservation practice factor and adjust the other factors. Extensive data collection and analysis were performed to make the USLE applicable to all areas of the United States east of the Rocky Mountains (105th meridian). Work has continued on modifying the parameters to allow use in the western states.

The USLE is:

$$A = RKLSCP \quad \text{[Eq 12]}$$

where LS = average annual soil loss (tons/acre/year)
R = rainfall factor (ft-tons/acre-in.)
K = soil erodibility factor (in./yr-ft)
LS = length-slope factor (unitless ratio)
C = cropping and management factor (unitless ratio)
P = conservation practice factor (unitless ratio).

As originally formulated, the USLE was designed to predict long-term average annual erosion rates for

[25] G. R. Foster and W. H. Wischmeier.

[26] W. H. Wischmeier and D. D. Smith, *Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains*, Agriculture Handbook, No. 282 (ARS, USDA, 1960); W. H. Wischmeier, *Procedures for Computing Sheet and Rill Erosion on Project Areas*, USDA SCS Tech Release #51, Rev. 2 (September 1977); W. H. Wischmeier and D. D. Smith, *Predicting Rainfall-Erosion Losses—A Guide to Conservation Planning*, Agric. Handbook No. 537 (USDA, 1978).

cropland. It has been modified to use with forests, rangeland, pasture, and idle land. The R factor has also been modified to work for single storms. However, since the equation was developed for estimating long-term average annual soil loss, it is less accurate for predicting specific events. Agriculture Handbook No. 537 describes the use of the USLE.[27] For non-agricultural uses of this equation, methods of determining the various factors are summarized in Figures 9 through 12 and Tables 2 through 6.

Four USLE analysis options were chosen to provide a variety of tools to meet Army needs. The Average Annual USLE represents the standard method whereas the other three options require variations in factor determination. Table 7 shows the methods of determining factors for the four options.

The Average Annual USLE option is for use in general soil loss analysis of selected areas when long-tern averages are good enough. It is a quick "first look" tool and can be used to assess the relative magnitude of soil loss. It is also suited for use with agricultural areas.

The Interval USLE option allows the user to assess soil loss when the time-frame of interest is other than average annual. The interval can range from a single storm to any other period up to 1 year. In using the Interval USLE option, the R factor represents either (1) the total interval erosivity or (2) the erosivity of the maximum rainfall for a single storm expected during the interval. This permits the introduction of risk as a factor in soil loss prediction. For example, the user can determine the soil loss associated with the 2-year rainfall or, expressed another way, the soil loss from the rainfall that has a 50 percent chance of occurring in any given year. Historical rainfall records provide a data base that can be manipulated to provide the interval or maximum storm rainfall R factors.

For construction sites, the Construction USLE option can be used. This option is especially suited for predicting soil-loss and sediment concentrations in receiving waters as a result of construction activities. It combines the R factor of the Interval option with additional subroutines to determine the K and LS factors. It includes a method to compute sediment transport from the construction site to a receiving channel and computes the resulting sediment concentration using a mass balance equation. This option works only for single storms.

[27] W. H. Wischmeier and D. D. Smith, 1978.

The Runoff option extends the predictive ability from soil loss to overland sediment transport. A common criticism of the USLE is that it predicts only soil loss, not the amount of sediment reaching the channel system. This option replaces the R factor with either of two factors derived from runoff so that the results more closely reflect the amount of sediment leaving the study area. One factor, developed by Williams, is most applicable for areas in the Southwest. The other, developed by Onstad and Foster, was tested in areas of the Midwest. These factors predict soil delivered to the channel system.

Physical Process Models

As interest has grown in the origin of pollutants in a watershed, the need has arisen for models that more closely represent the physical processes at work. The USLE and its modifications average soil loss across the watershed. To effectively predict the impact of changing land use, however, a model must simulate the physical response of the watershed more accurately and for smaller areas.

Several techniques have been developed that combine erosion models with watershed models.[28] Using simulated flow from the watershed model, sediment is routed over the land surface and, in some models, through the channel system as well. A model developed at Colorado State University (CSU) represents the current state of the art for predicting sediment yield from small watersheds.[29] The model was originated by Li[30] and has been modified and tested by Simons, Li, and Stevens; Li, Simons, and Simons; and Shiao.[31] The model is well documented and has guidance for estimating input parameters.[32]

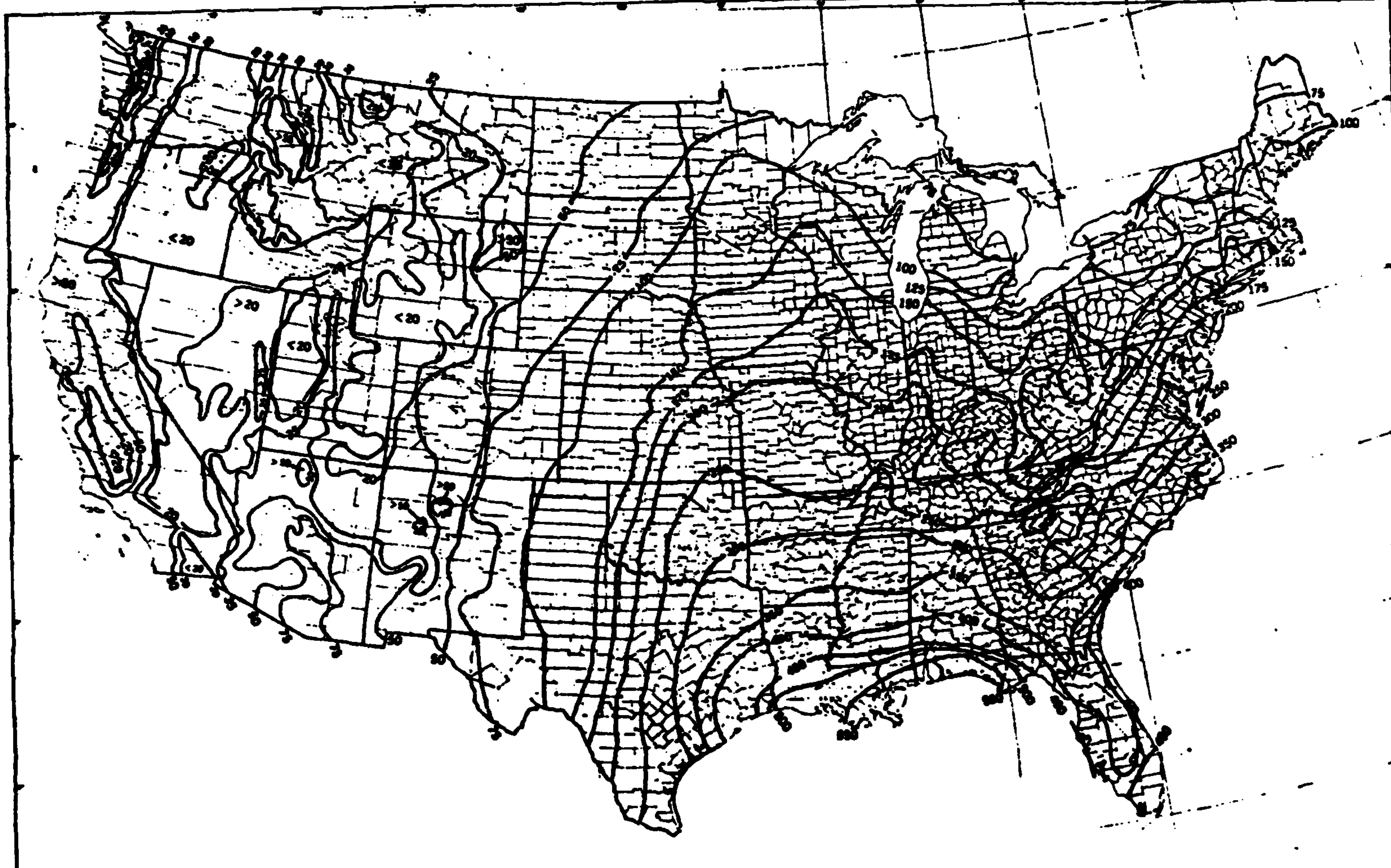
[28] W. P. David and C. E. Beer; *Sediment-Erosion Transport–Deposition Simulation–State-of-the-Art in Present and Prospective Technology for Predicting Sediment Yields and Sources*, ARS-S-4 (June 1975), pp 274-285; M. A. Negev, *Sediment Model on a Digital Computer*, Technical Report No. 76 (Department of Civil Engineering, Stanford University, 1967).

[29] L. Y. Shiao, *Water and Sediment Yield and Small Watersheds*, Ph.D. Dissertation (Colorado State University, 1978).

[30] R. M. Li, *Mathematical Modeling of Response from Small Watersheds*, Ph.D. Dissertation (Department of Civil Engineering, Colorado State University, Fort Collins, CO).

[31] D. B Simons, R. M. Li, and M. A. Stevens, *Development of Models for Predicting Water and Sediment Routing and Yield from Storms on Small Watersheds* (USDA Forest Service, Rocky Mountain Forest and Range Expt. Station, August 1975); R. M. Li, R. K. Simons, and D. B. Simons, "A Generalized Kinematic Wave Approximation for Flood Routing (Submitted to *J. Hydraul. Div. ASCE*, 1977); L. Y. Shiao.

[32] D. B. Simons, et al., 1979.



[1]Measured in EI units—(100 foot tons/acre) (inches/hour).

Figure 9. Erodent Map—Average annual values of the rainfall erosion index R (from W. H. Wischmeier and D. D. Smith, *Predicting Rainfall Erosion Losses – A Guide to Conservation Planning*, Agric. Handbook No. 537 [U.S. Dept. of Agric., 1978]).

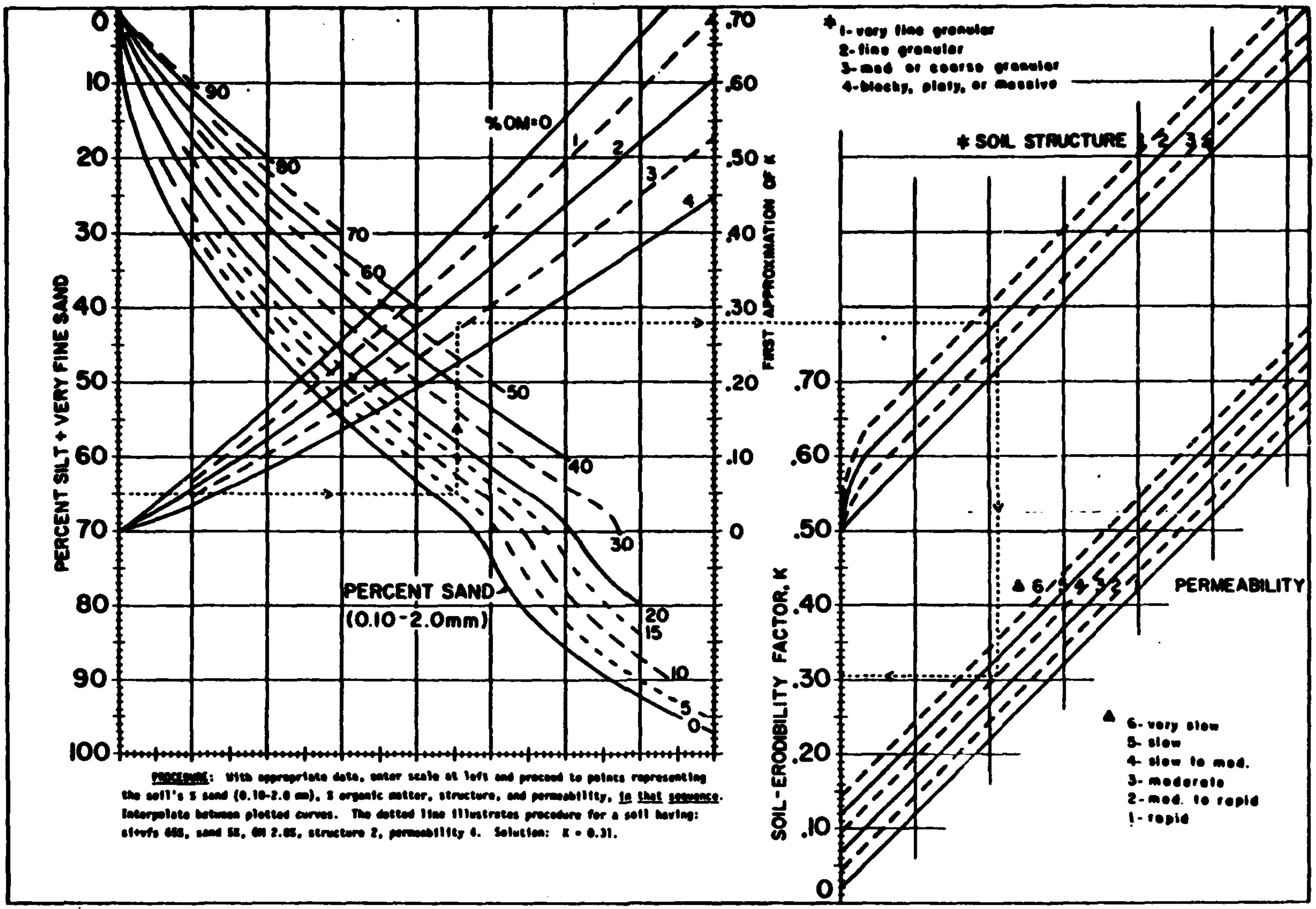


Figure 10. The erodibility K Nomograph (from W. H. Wischmeier and D. D. Smith, *Predicting Rainfall Erosion Losses–A Guide to Conservation Planning).*

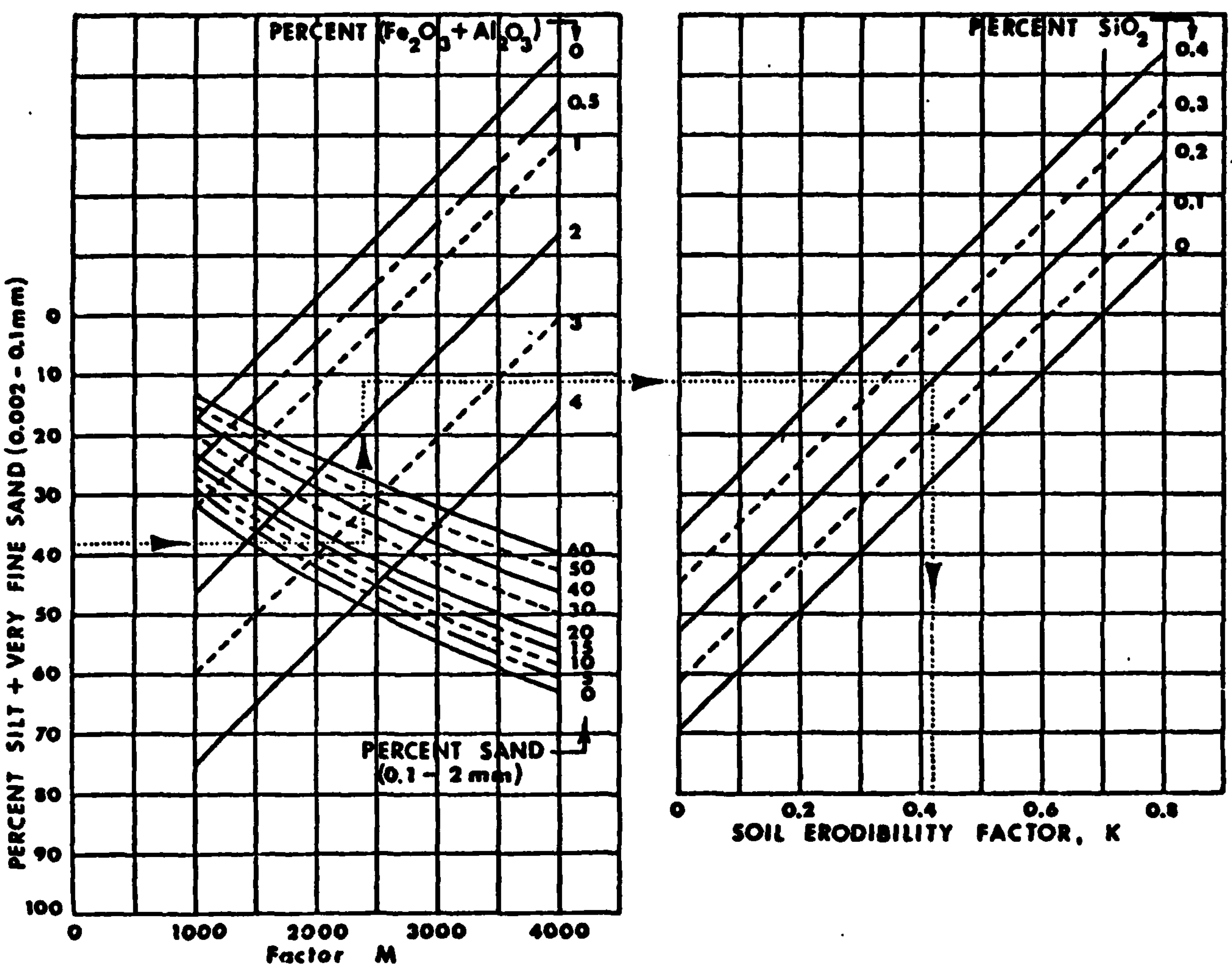


Figure 11. Nomograph for estimating the erodibility factor, K, of subsoils with high clay content (from W. H. Wischmeier and D. D. Smith. *Predicting Rainfall Erosion Losses–A Guide to Conservation Planning).*

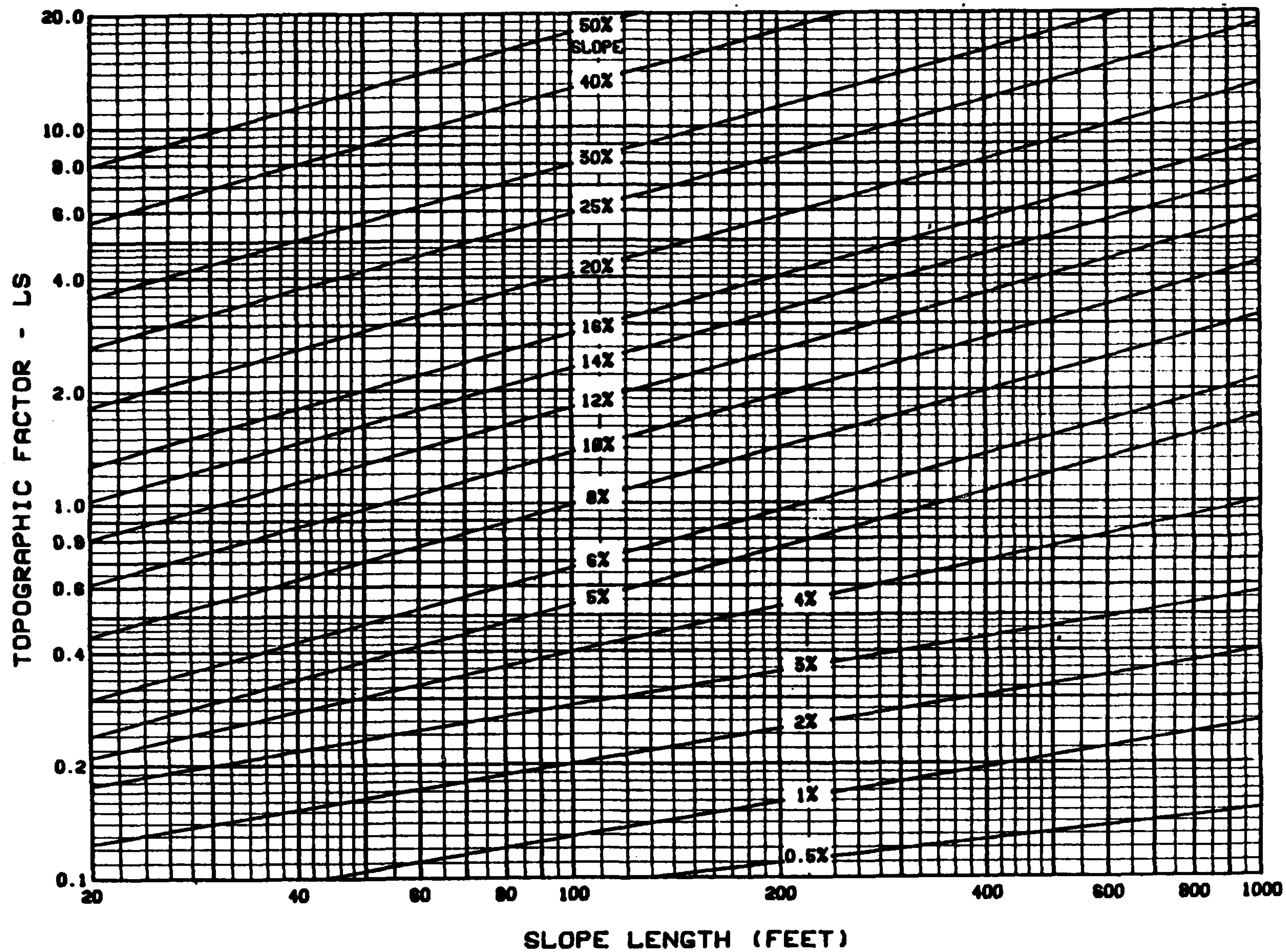


Figure 12. Slope-effect chart (topographic factor, LS) (from W. H. Wischmeier and D. D. Smith, *Predicting Rainfall Erosion Losses–A Guide to Conservation Planning*).

Table 2

Factor C for Permanent Pasture, Range, and Idle Land*

Type and height**	*Vegetative Canopy* Percent cover***	Type+	*Cover that contacts the soil surface* *Percent ground cover* 0	20	40	60	80	95+
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	.45	.24	.15	.091	.043	.011
Tall weeds or short brush with average drop falling height of 20 in.	25	G	.36	.17	.09	.038	.013	.003
		W	.36	.20	.13	.083	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Appreciable brush or bushes, with average drop falling height of 6-1/2 ft	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.087	.042	.011
	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees, but no appreciable low brush. Average drop falling height of 13 ft	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.089	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.084	.041	.011

*The listed C values assume that the vegetation and mulch are randomly distributed over the entire area. Source: W. H. Wischmeier and D. D. Smith, 1978.

**Canopy height is measured as the average distance of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to drop falling height and is negligible if falling height exceeds 33 ft.

***Portion of total-area surface that would be hidden from view by canopy in a vertical projection (a bird's-eye view).

+G: cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 in. deep. W: cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral-root network near the surface), undecayed residues, or both.

Table 3

Mulch Factors and Length Limits for Construction Slopes*

Type of mulch	Mulch rate (tons/acre)	Land slope (percent)	Factor C	Length limit** (ft)
None	0	all	1.0	--
Straw or hay,	1.0	1-5	0.20	200
tied down by	1.0	5-10	.20	100
anchoring and	1.5	1-5	.12	300
tacking	1.5	6-10	.12	150
equipment***	2.0	1-5	.06	400
Do.	2.0	6-10	.06	200
	2.0	11-15	.06	150
	2.0	16-20	.11	100
	2.0	21-25	.14	75
	2.0	26-33	.17	50
	2.0	34-50	.20	35
Crushed stone,	135	<16	.05	200
1/4 to 1-1/2 in.	135	16-20	.05	150
	135	21-33	.05	100
	135	34-50	.05	75
Do.	240	<21	.02	300
	240	21-33	.02	200
	240	34-50	.02	150
Wood chips	7	<16	.08	75
	7	16-20	.08	50
Do.	12	<16	.05	150
	12	16-20	.05	100
	12	21-33	.05	75
Do.	25	<16	.02	200
	25	16-20	.02	150
	25	21-33	.02	100
	25	34-50	.02	75

*Developed by an interagency workshop group on the basis of field experience and limited research data. Source: W. H. Wischmeier and D. D. Smith, 1978.

**Maximum slope length for which the specified mulch rate is considered effective. When this limit is exceeded, either a higher application rate or mechanical shortening of the effective slope length is required.

***When the straw or hay mulch is not anchored to the soil, C values on moderate or steep slopes of soils with K values greater than 0.30 should be taken at double the value given in this table.

Table 4

Factor C for Undisturbed Forest Land*

Area covered by canopy of trees and undergrowth (percent)	Area covered by duff at least 2 in. deep (percent)	Factor C**
100-75	100-90	.0001-.001
70-45	85-75	.002-.004
40-20	70-40	.003-.009

*Where effective litter cover is less than 40 percent or canopy cover is less than 20 percent, use Table 6. Also use Table 6 where woodlands are being grazed, harvested, or burned. Source: W. H. Wischmeier and D. D. Smith, 1978.

**The ranges in listed C values are caused by the ranges in the specified forest litter and canopy covers and by variations in effective canopy heights.

Table 5

Factor C for Mechanically Prepared Woodland Sites*

Site Preparation	Mulch cover** (percent)	Soil condition*** and weed cover+: Excellent NC	Excellent WC	Good NC	Good WC	Fair NC	Fair WC	Poor NC	Poor WC
Disked, raked, or bedded++	None	0.52	0.20	0.72	0.27	0.85	0.32	0.94	0.36
	10	.33	.15	.46	.20	.54	.24	.60	.26
	20	.24	.12	.34	.17	.40	.20	.44	.22
	40	.17	.11	.23	.14	.27	.17	.30	.19
	60	.11	.08	.15	.11	.18	.14	.20	.15
	80	.05	.04	.07	.06	.09	.08	.10	.09
Burned+++	None	.25	.10	.26	.10	.31	.12	.45	.17
	10	.23	.10	.24	.10	.26	.11	.36	.16
	20	.19	.10	.19	.10	.21	.11	.27	.14
	40	.14	.09	.14	.09	.15	.09	.17	.11
	60	.08	.06	.09	.07	.10	.08	.11	.08
	80	.04	.04	.05	.04	.05	.04	.06	.05
Drum-chopped+++	None	.16	.07	.17	.07	.20	.08	.29	.11
	10	.15	.07	.16	.07	.17	.08	.23	.10
	20	.12	.06	.12	.06	.14	.07	.18	.09
	40	.09	.06	.09	.06	.10	.06	.11	.07
	60	.06	.05	.06	.05	.07	.05	.07	.05
	80	.03	.03	.03	.03	.03	.03	.04	.04

*Source: W. H. Wischmeier and D. D. Smith, 1978.

**Percentage of surface covered by residue in contact with the soil.

***Excellent soil condition -highly stable soil aggregates in topsoil with fine tree roots and litter mixed in. Good--moderately stable soil aggregates in topsoil or highly stable aggregates in subsoil (topsoil removed during raking), only traces of litter mixed in. Fair–highly unstable soil aggregates in topsoil or moderately stable aggregates in subsoil, no litter mixed in. Poor–No topsoil, highly erodible soil aggregates in subsoil, no litter mixed in.

+NC–No live vegetation. WC–75 percent cover of grass and weeds with an average drop falling height of 20 in. For intermediate percentages of cover, interpolate between columns.

++Modify the listed C values as follows to account for effects of surface roughness and aging: First year after treatment–multiply listed C values by 0.40 for rough surface (depressions > 6 in.); by 0.65 for moderately rough; and by 0.90 for smooth (depressions < 2 in.). For 1 to 4 years after treatment–multiply listed factors by 0.7. For 4+ to 8 years; use Table 6. More than 8 years; use Table 7.

+++For first 3 years, use C values as listed. For 3+ to 8 years after treatment, use Table 6. For more than 8 years after treatment, use Table 7.

Table 6

Factor P for Construction Sites*

Small sediment basins. Those with inflow-to-capacity ratios of 0.03 to 0.04 result in an average trap efficiency of 70 percent. This will yield a P value of 0.3 if the whole construction site is served by sediment basins.

Downstream sediment basins. Larger size basins constructed downstream of the construction site with inflow-to-capacity ratio of 0.07 will have a trap efficiency of 80 percent and a corresponding P value of 0.20.

Erosion reducing structures. Diversion berms, sodded ditches, interceptor berms, grade stabilization structures, and level spreaders are collectively called erosion reducing structures. The overall effectiveness of erosion reducing structures is estimated at 50 percent. The factor P for this normal usage then is 0.5. For higher usage, erosion reducing structures are estimated to be 60 percent effective, giving a P factor value of 0.40.

*Without the use of structural control measures, the P-factor, should be set equal to 1.0 at construction sites. Source: E. L. Hotes, K. H. Ateshian, and B. Skeikh, *Comparative Costs of Erosion and Sediment Control,* EPA 430N9-73-016 (EPA, July 1973).

Table 7

USLE Options

Routine	R1	R2	R3	R4	R5	K1	K2	C	P	LS1	LS2
Avg. Annual	X					X		X	X	X	
Interval			X			X		X	X	X	
Construction		X	X			X	X	X	X		X
Rain/Runoff				X	X	X		X	X	X	

R1 Determines average annual from files (Isoerodent Map Fig. 11)

R2 Calculate by Hotes depth/duration method $R = \frac{aD^b}{H^c}$

R3 Calculate by depth/duration frequency analysis method

R4 Calculate by Williams' method, $R = \left(11.8\,(Qq^{p})^{.56}\right)$ *

R5 Calculate by Onstad-Foster method, $R = 0.5\,EI + 15\,Qq_p^{1/3}$*

K1 Determine from files using soil series name***
K2 Calculate by nomogram equation (AG. HDBK 537)**,***
C Present tables from files***
P Present table from files
LS1 Calculate by contour-extreme point and contour-length method+
LS2 Must calculate by slope length method (no option for direct entry)++

*Requires watershed runoff model (SCS, curve no. USDAHL)

**May require field measurement of some soil properties.

***Can be weighted to average across watershed.

+J. R. Williams and H. D. Berndt.

++W. H. Wischmeier and D. D. Smith, 1978.

Simons, Li, and Stephens provide the following general description of the model.

> The Colorado State University model simulates the land surface hydrologic cycle, sediment production, and water and sediment movement on small watersheds. Conceptually the watershed is divided into an overland flow part and a channel system part. Different physical processes are important for the two different environments. In the overland flow part, processes of interception, evaporation, infiltration, raindrop impact detachment of soil, erosion by overland flow, and overland flow water and sediment routing to the nearest channel are simulated. In the channel system part, water and sediment contributed by overland flow are routed and the amount of channel erosion or sediment deposition through the channel system is determined. The version used in this study does not simulate evaporation since it is a single storm event model.[33]

Figure 13 depicts the CSU model structure. Interception losses are calculated as a function of canopy and ground cover with their respective water-holding capacities and are subtracted from precipitation to determine rainfall excess. The Green-Ampt equation is used to determine infiltration rates, and if rainfall intensity is greater than the infiltration rate, runoff occurs.

Water is routed using a numerical solution to the continuity equation, with a kinematic wave assumption for the momentum equation. This approach applies to both overland and channel flow. The continuity equation is:

$$\frac{\delta Q}{\delta X} + \frac{\delta A}{\delta t} = q_\ell \qquad \text{[Eq 13]}$$

where Q = discharge
X = downslope distance
A = flow area
t = time
q_ℓ = lateral inflow (rainfall) or surface flow.

Two processes are involved in sediment routing: (1) balancing the sediment transport and sediment supply rate and, (2) the effect of armoring on sediment

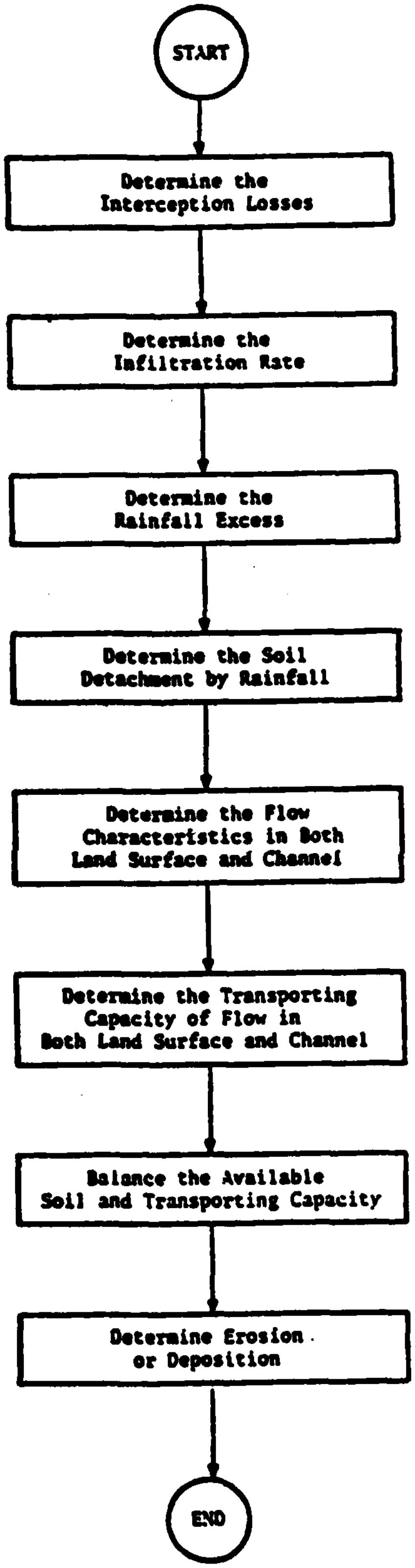


Figure 13. Structure of the CSU model (from L. Y. Shiao).

[33] D. B. Simons, et. al., 1975.

transport rates. The combination of the Meyer-Perer and Muller bedload equation and Einstein's suspended load procedure is used to determine transport capacity. The potential rate of soil detachment by raindrop impact is represented by a power function of rainfall intensity as already provided. The percentages of sediment size on the surface are adjusted with time to account for armoring effects, and the amount of soil transported by runoff is found by comparing total transport capacity to total available amount of loose soil. The continuity equation for sediment is solved to determine aggradation and degradation.

The model requires four categories of input data: climatological, watershed geometry, physical features, and soil hydraulics. Specific items are listed in Table 8. Shiao found that for watersheds with small water yields, permeability and average suction have the most influence.[34] For a watershed with a high water yield, the total channel resistance coefficient and the channel grain resistance coefficient are most influential. Rainfall detachment has little or no influence on sediment yield. The model simulates runoff volume better than sediment yield or peak discharge; moreover, it simulates water hydrology better for summer than winter.

5 SYSTEM STRUCTURE FOR IMPACT PREDICTION TECHNIQUES

The soil erosion models to be used in developing a predictive system for training lands must be structured around the constraints affecting use of such a system. Examining these constraints also shows the framework within which the system must operate. Three types of constraints must be examined: objective, operational, and model.[35]

Objective constraints include:

- The type of environmental impacts the model will address.
- The anticipated situations for which analysis is needed
- The level of complexity needed to attain reasonable results.

Operational constraints deal with:

- The user's experience with computers
- When and how models might be used in impact analysis
- How model data bases should be developed and maintained
- How the model system fits with other systems in CERL's ETIS.

Model constraints include:

- The complexity of available models
- The relative data requirements between models
- Software availability
- Hardware requirements.

Objective Constraints

Comprehensive training area impact prediction at Army installations should include techniques to quantify all of the physical, chemical, and biological processes involved. These range from activities leading to soil loss through the effects on ecosystems. The stages can be classified as:

1. Disturbance of soil and destruction of ground cover

2. Soil Loss

3. Sediment transport and deposition

4. Chemical transport

5. Effects on the ecosystem.

Table 8

Data Requirements for the CSU Model

Climatological	Rainfall intensity and duration Temperature
Watershed geometry	Dimensions and slopes of watershed Cross-sectional area measurements for stream channels
Physical features	Ground cover Soil particle size and distribution Vegetation friction coefficients
Soil Hydraulics	Porosity Antecedent moisture Suction head Permeability

[34] L. Y. Shiao.

[35] R. E. Riggins and E. D. Smith, *Aquatic Rational Threshold Value (RTV) Concepts for Army Environmental Impact Assessment*, TR N-74/ADA073032 (CERL, July 1979).

The techniques described in this report relate to processes 2 and 3. Work is continuing on analytical techniques for the other processes.

Range officers, land managers, and environmental office personnel can use the techniques to: (1) calculate long-term average annual soil loss; (2) calculate soil loss for an interval during the year; (3) predict soil loss over an interval with a given probability (risk); (4) predict soil loss for a single storm with a given probability and adjust with a delivery ratio to predict yield; (5) predict sediment yield for a single storm from a watershed; and (6) predict sediment yield, identify sources, and route through a channel system.

Operational Constraints

Operational constraints include the factors involved with using analytic techniques such as user capabilities. For example, methods must be designed for persons with little or no practical knowledge of erosion processes. Simplicity and minimum input data are also requirements and, most important, the techniques must provide information useful in decision-making.

Other operational constraints for an erosion model system are data maintenance; the frequency of data update and the difficulty of data acquisition; storage and retrieval of data; comprehensiveness of use among varied situations and ecosystems; and model degree of resolution, calibration, fine-tuning, accuracy, and precision.

Model Constraints

The complexity of available analytic techniques has been discussed throughout this report. The primary goal is to establish an appropriate trade-off between model complexity and accuracy.

System Structure

Figure 14 shows the system structure. A model system consists of three major parts: process guidelines, analytic tools, and supporting data base. Process guidelines include the procedures a user needs to choose among model options, understand the intent of the models, and interpret model output. Analytic tools include the various techniques described in this report for calculating soil loss and sediment transport. The data base is that information needed to support model analysis. There are essentially three types of erosion analysis functions in this system: the USLE, the modified USLE (MUSLE) which replaces or adjusts the rainfall factor with runoff, and the CSU model which gives a more precise picture of watershed processes. In Figure 14, the level of model complexity and difficulty of use increase downward.

Analytic Tools

The analysis routines for USLE vary according to how the R factor is calculated. The Average Annual Routine uses an R value taken from the isoerodent map. The Interval and Single Storm Routines use the intensity method.[36] For the Interval Routine, individual storm values are summed to obtain an R factor value for the interval.

To calculate the sediment reaching the receiving waters, a delivery ratio must be applied to the USLE. A universal ratio does not exist; however, the one developed by Bhutani, et al., can be used.[37] A delivery ratio is most likely to be used for erosion analyses at construction sties.

The maximum concentration of sediment in receiving waters can be determined if peak flow is known. The unit hydrograph method offers a simple, effective way to calculate peak flow from small watersheds.[38]

In the MUSLE, the R factor is replaced by a factor that incorporates runoff. The Runoff Yield Routine uses the runoff factor developed by Williams and Berndt.[39] It is most suitable for watersheds in the Southwest since data from such areas were used to determine the coefficients. Williams and Hann developed a computer program called HYMO to compute total volume and peak flow rates.[40] Onstad and Foster used a watershed runoff program developed by the Department of Agriculture Hydrologic Laboratory.[41] Detailed descriptions of the rainfall-runoff models may be found in the literature.

The CSU model is more complex and is used when more precise identification of sediment sources in the watershed must be determined. It has capability for evaluating the effects of changing watershed land use on soil loss and sediment transport. It also allows users to see the effects of routing sediment through channel systems.

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[36] E. L. Hotes, et al.

[37] J. Bhutani, et al.

[38] *National Engineering Handbook*, Section 4, "Hydrology," NEH Notice 4 (Soil Conservation Service, USDA, 1972).

[39] J. R. Williams and H. D. Berndt.

[40] J. R. Williams and R. W. Hann, *HYMO: Problem-Oriented Computer Language for Hydrologic Modeling Users Manual*, USDA ARS-S-9 (USDA, May 1973).

[41] H. N. Holtan, et al., USDAHL-74, "Reversed Model of Watershed Hydrology," *USDA Tech. Bull.*, No. 1518 (USDA, December 1975).

Process Guidelines:

4 — Present options
5 — Prompt for input data
3 — Help routines
2 — User guidelines
6 — Output description
1 — Access procedures

Analytical Tools:

Analysis Topic	Analysis Functions	Analysis Routines
	USLE	Annual Soil Loss (Aug)
		Interval Soil Loss (with or without probability)
		Construction (Single Storm Soil Loss with Given Probability, Adjusted with Delivery Ratio to Calculate Sediment Concentration in Receiving Stream)
Physical Land Degradation		Runoff Yield for a Single Storm using MUSLE (Williams)[33]
		Rainfall-Runoff Yield for a Single Storm Using Onstad and Foster's Method[18]
	CSU	

Data Base:

0 Climate
0 Soils
0 Watershed geometry
0 Channel geometry

0 User files

Figure 14. System structure for physical degradation models.

6 CONCLUSION

Army training lands can be improved physically when land managers are better able to identify maintenance needs based on predicted degradation. This report describes the analytic techniques chosen for predicting physical degradation of training areas. A model system has been developed to incorporate the various techniques into a comprehensive predictive methodology. When complete, this system will provide a user-friendly series of computer programs for use at all Army installations. The program will also be added to CERL's Environmental Technical Information System (ETIS). As this research progresses, similar systems will be developed for predicting chemical and biological degradation at Army training grounds.

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